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Fifth Quarterly Report

STUDY PROGRAM ON (30 - 100 GHz) ELECTRONICALLY STEERABLE ANTENNA SYSTEMS

20 July 1967 - 20 October 1967

Contract NAS 5-10256

Prepared for

Applications Experiments Branch
Goddard Space Flight Center
Greenbelt, Maryland

ADVANCED TECHNOLOGY CORPORATION

1830 YORK ROAD TIMONIUM, MARYLAND

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Prepared by

John M. Cotton, Jr.

and

Dennis E. Grimes

ADVANCED TECHNOLOGY CORPORATION
1830 York Road
Timonium, Maryland
21093

for

Applications Experiments Branch
Goddard Space Flight Center
Greenbelt, Maryland

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1. INTRODUCTION

The four previous quarterly reports on this program have summarized studies made to determine optimum phased array techniques for use at millimeter wavelengths. The specific application is to be a satellite borne electronically steerable antenna. After a comprehensive survey of available techniques, the study continued with an elimination process which reduced the number of recommended approaches to six. Five of these six employ phase shifting the r.f. either at the transmitting frequency, or at the sub-harmonic, while the last uses retrodirective techniques accomplishing the phase shifting at IF.

Three of the six were selected for further study including actual design and experimental development of a feasibility model at 35 GHz. These three have a common radiating aperature -- an array which remains filled, but in the light of the limiting steering requirements can employ a smaller number of higher gain elements.

This report summarizes the results of the experimental work done in this quarter on various aspects of the antenna system. Utilizing the data accumulated from previous experimental work, three of the series feed arms to be employed in the feasibility model were fabricated and preliminary tests have been completed. In addition to this, work has also been done on the design and fabrication of a phase corrected optical feed system.

2. SERIES FEED SYSTEM

The feasibility model of the antenna array using a series feed is depicted in Figure 1. Power division will be accomplished through the use of eight identical sections -- one being used to excite the other seven, and the seven in turn feeding the 49 element output array. In general, the coupling to the auxiliary arms is achieved through the use of broadwall slots. The requirement on the amplitude distribution, however, does not always permit this approach. The illumination of the array is an approximation to a cosine-on-a-pedestal distribution with a 10 dB taper. Hence, the last two ports of the series string have the requirement that the power being coupled out exceeds the power being transmitted through, The solutions of this problem and others associated with the feed fabrication are described in the following sections.

2.1 Fabrication

In the discussions which follow, references will be made to the various ports of the series feed by number, taken serially from the input end. One of the more difficult tasks, then, was the power split between ports six and seven, which required a 5 to 2 ratio, i.e. of the power arriving at port 6, we require 5/7 ths to be coupled out with the remainder going to port 7 via a standard mitered bend. This 1.5 dB coupling requirement is not difficult except under the self-imposed constraint here that the length of the feed structure be no more than the aperture size, namely 16λ.

The solution of this took the form of what might be called a "leaky mitered bend" which consists of a fixture that has the capability of changing the standard mitered wall to one with an iris in the center. This allows a certain amount of power to leak through while reflecting most of the power around the bend. The test fixture which

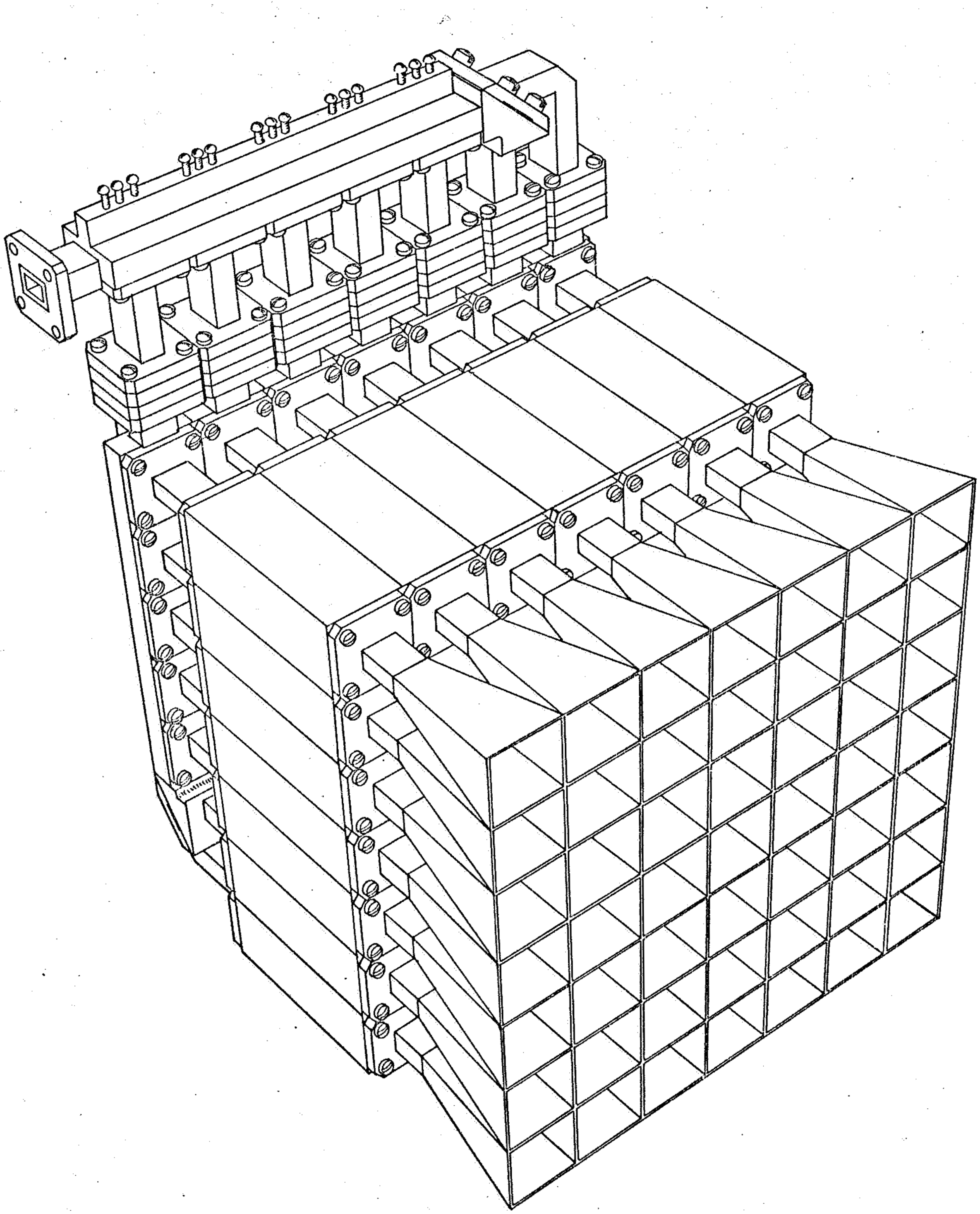

FIG. 1 - FEASIBILITY MODEL OF ARRAY USING A CORPORATE FEED

was made is shown in Figure 2. The tests performed, as previously reported, indicated that the desired coupling could indeed be achieved with this device. The series feed structure was then designed and fabricated using broadwall slots as couplers for the first five ports and the leaky mitered bend at the sixth port to couple power to the sixth and seventh ports as shown schematically in Figure 3 and pictorially in Figure 4. An exploded view is shown in Figure 5. Since the effects of mutual coupling between ports in the section was not entirely known, the slot size for each of the broadwall couplers had to be determined experimentally starting at the last and working backwards to the first.

2.2 Experimental Development

Since the coupling coefficients are largest for the last three ports in each series feed section, they are the most difficult to achieve and therefore were determined first. The procedure for this is rather involved.

First a blank shim was inserted in place of the first five coupling ports and a blank shim in the leaky mitered bend (refer again to Figure 3). This, in effect, produced a long mitered bend -- through the feed section and out port 6 -- and allowed the insertion loss of the unit to be measured. Approximately 0.5 dB loss was expected through the section and was experimentally verified.

Next, a brass shim with a 2.9 dB slot at the fifth port but with no slots at the first four ports was inserted in the feed arm and various sizes of irises were placed in the leaky mitered bend. The entire unit was then matched to the input and the tuning screws (at the fifth port) locked in place. The power from each of ports 5, 6 and 7 was then measured with the other two terminated and the results are shown in Figure 6. It was noted that mutual coupling between the slot at port 5 and the iris at port 6 enhanced the coupling of the slot.

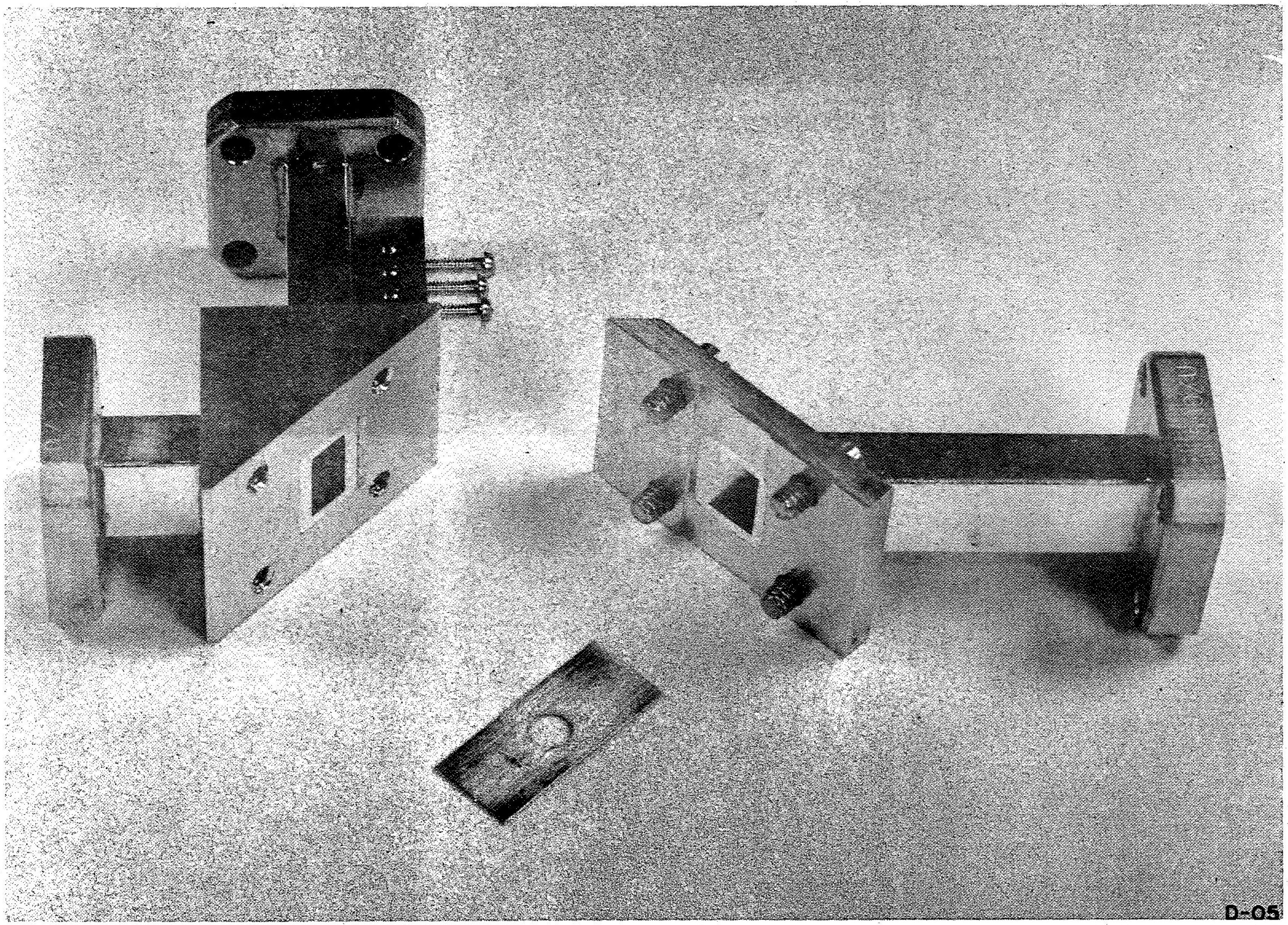

FIG. 2 - LEAKY MITERED BEND

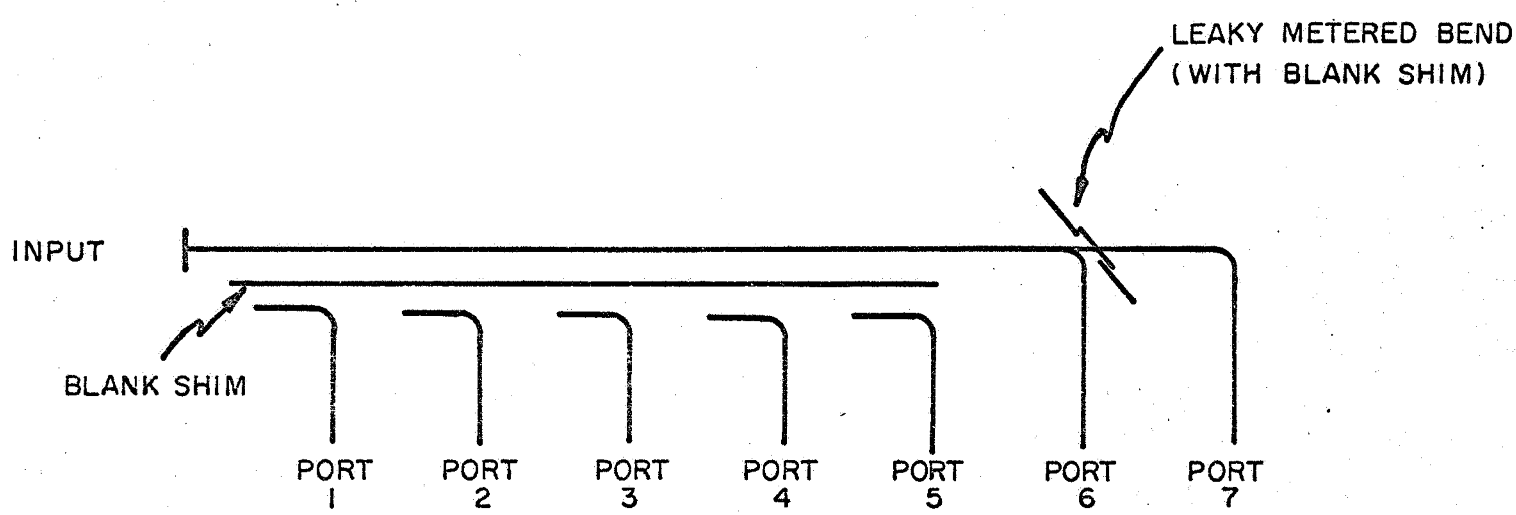

FIG.3-SCHEMATIC OF SERIES FEED SECTION

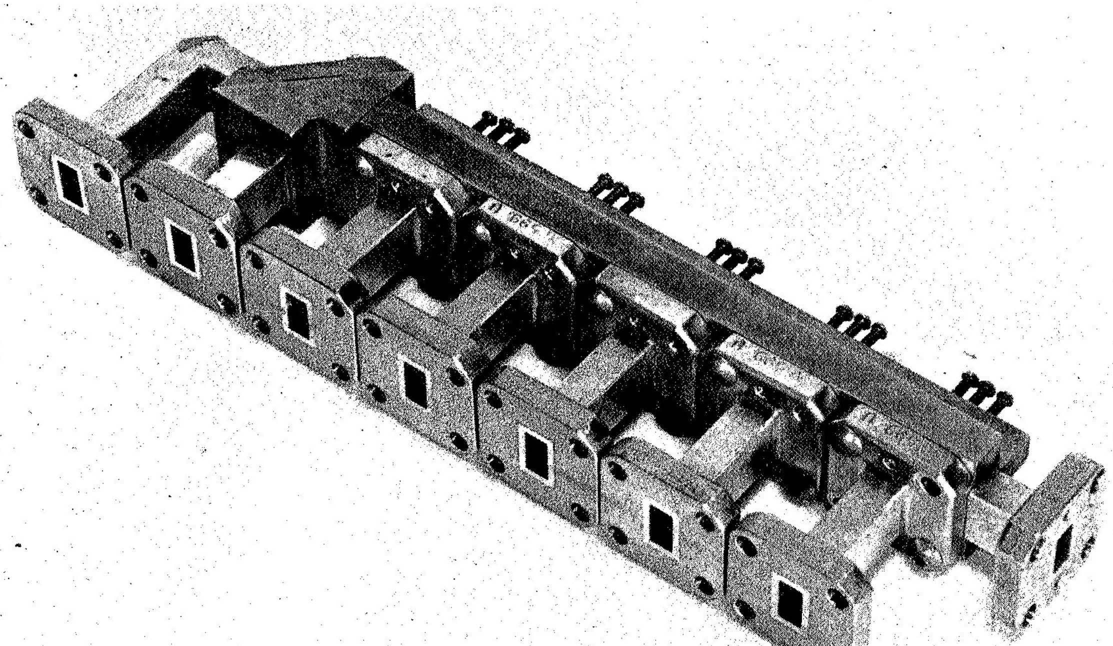

FIG. 4 - ASSEMBLED SERIES COUPLER FEED

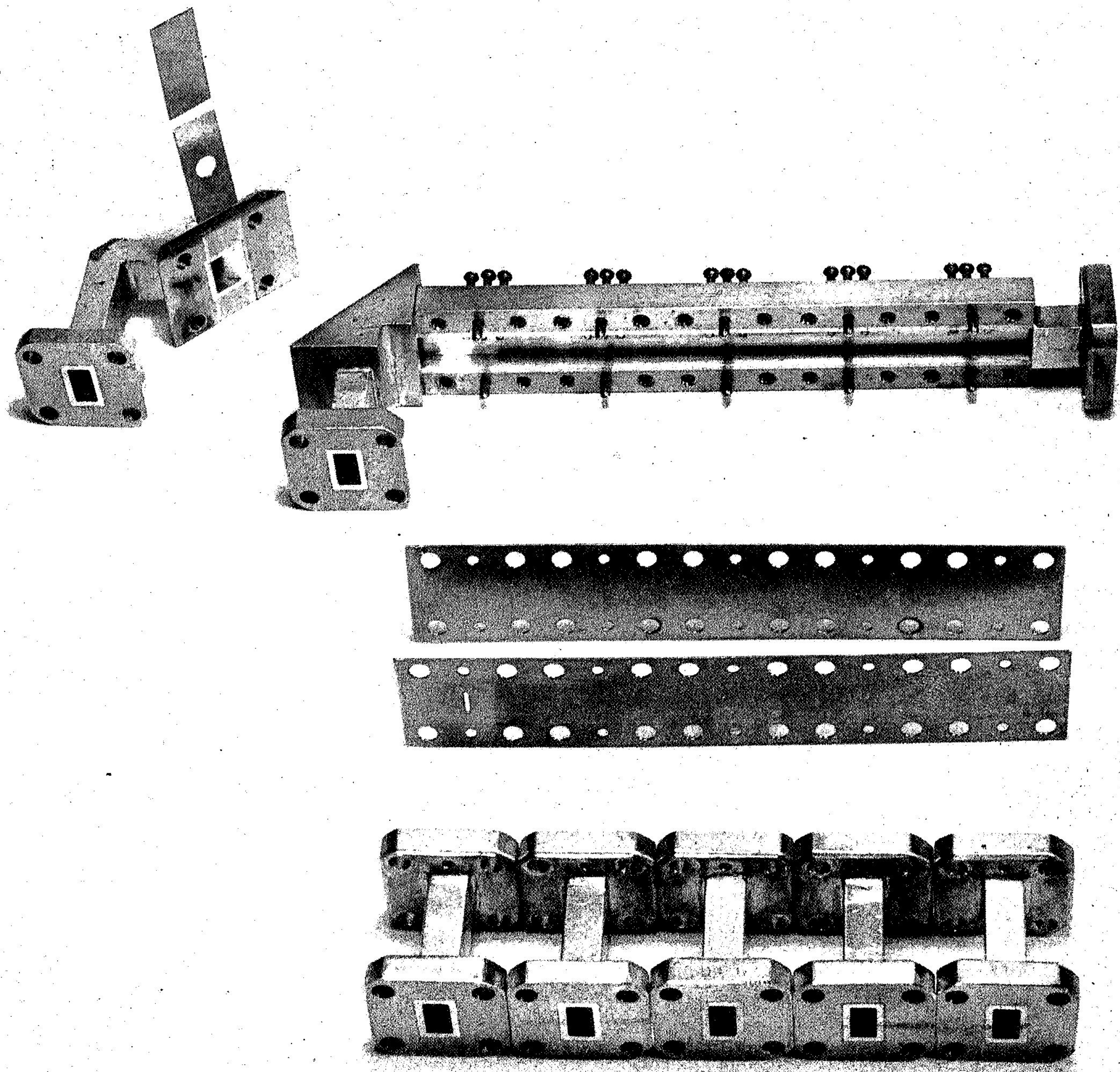

FIG. 5 - SERIES FEED COMPONENTS

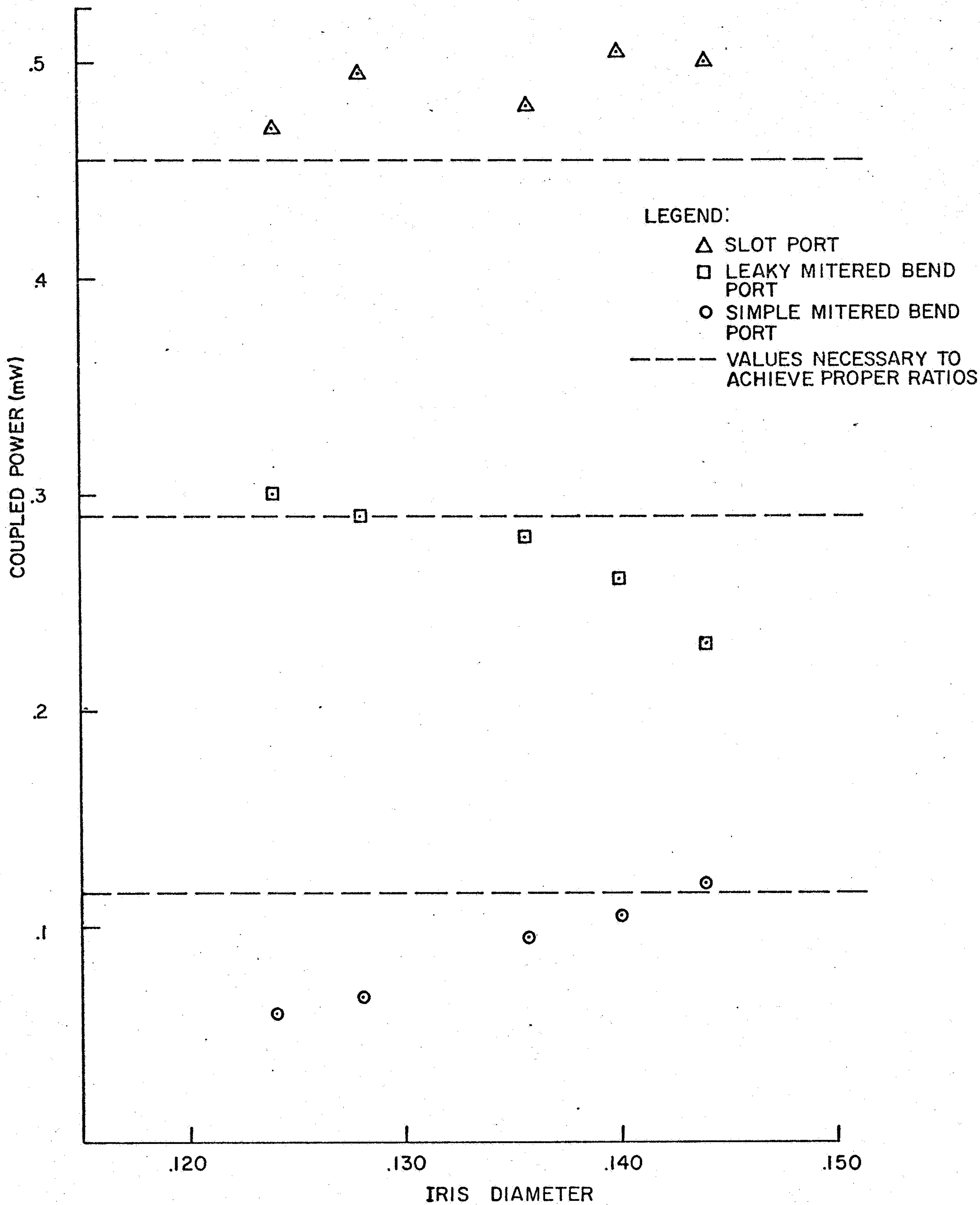

FIG. 6 –IRIS SIZE VS. COUPLED POWER

Therefore, smaller slot sizes were tried at the 5th port until the proper coupling was achieved. However, it was discovered that at the depth of insertion of the tuning screws to effect a match to the input is not unique. A wide variation of power levels at the fifth, sixth and seventh ports is obtainable by varying the penetration of the tuning screws at the fifth port (still maintaining a good match). So once the appropriate power levels are arrived at the screws are locked in place.

Similarly, once this is accomplished, the brass shim with the correct slot size at the fifth port is replaced by a similar one but with an additional slot -- at the fourth port, and the process repeated. Now the tuning problem has shifted to the fourth port. However, experimental data obtained to date show the range of variation possible at the fourth port is not as great as that encountered at the fifth port. Hence the problem is diminished somewhat. It is hoped that this trend will continue and by the time the first port is attempted the problem will be almost non-existant.

The difficulty of producing the proper power levels was alleviated to a large extent by a technique which was discovered for tuning the feed sections. It was noted that a good match could be obtained by using, of the three screws available at each of the first five ports, only the two screws nearest the input. Then the desired power could be obtained by adjusting only the third screw without greatly affecting the match produced by the first two screws. In fact, the greater penetration of the third screw, the less coupling at that port and consequently, the more power delivered to the higher numbered ports (See again Figure 3). Using this technique the time required to properly tune each port was reduced by 75%.

To date, only the coupling slots for the last four ports have been tested and the results are shown in Figure 7 and Figure 8.

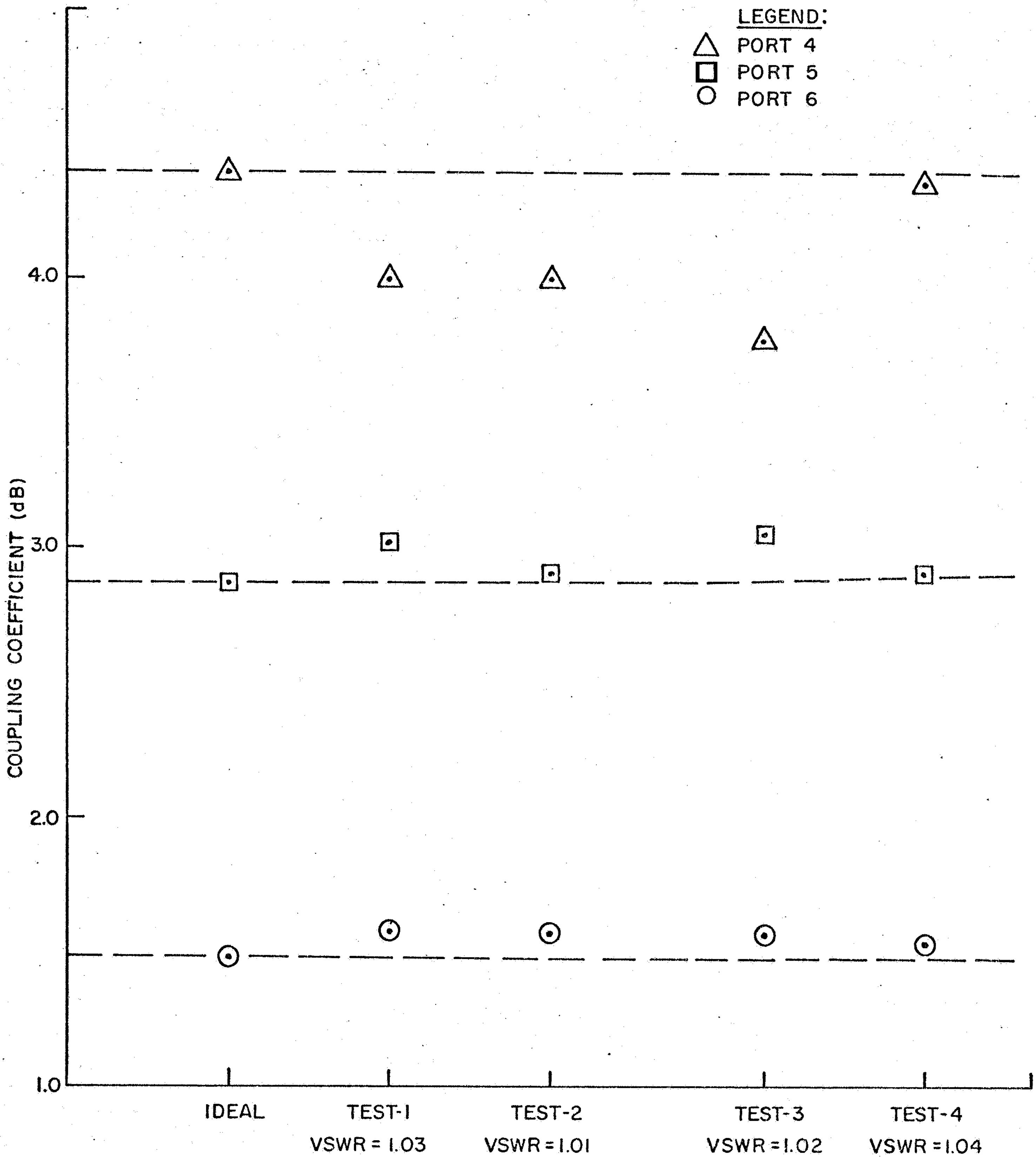

FIG. 7 TEST SECTION # 1

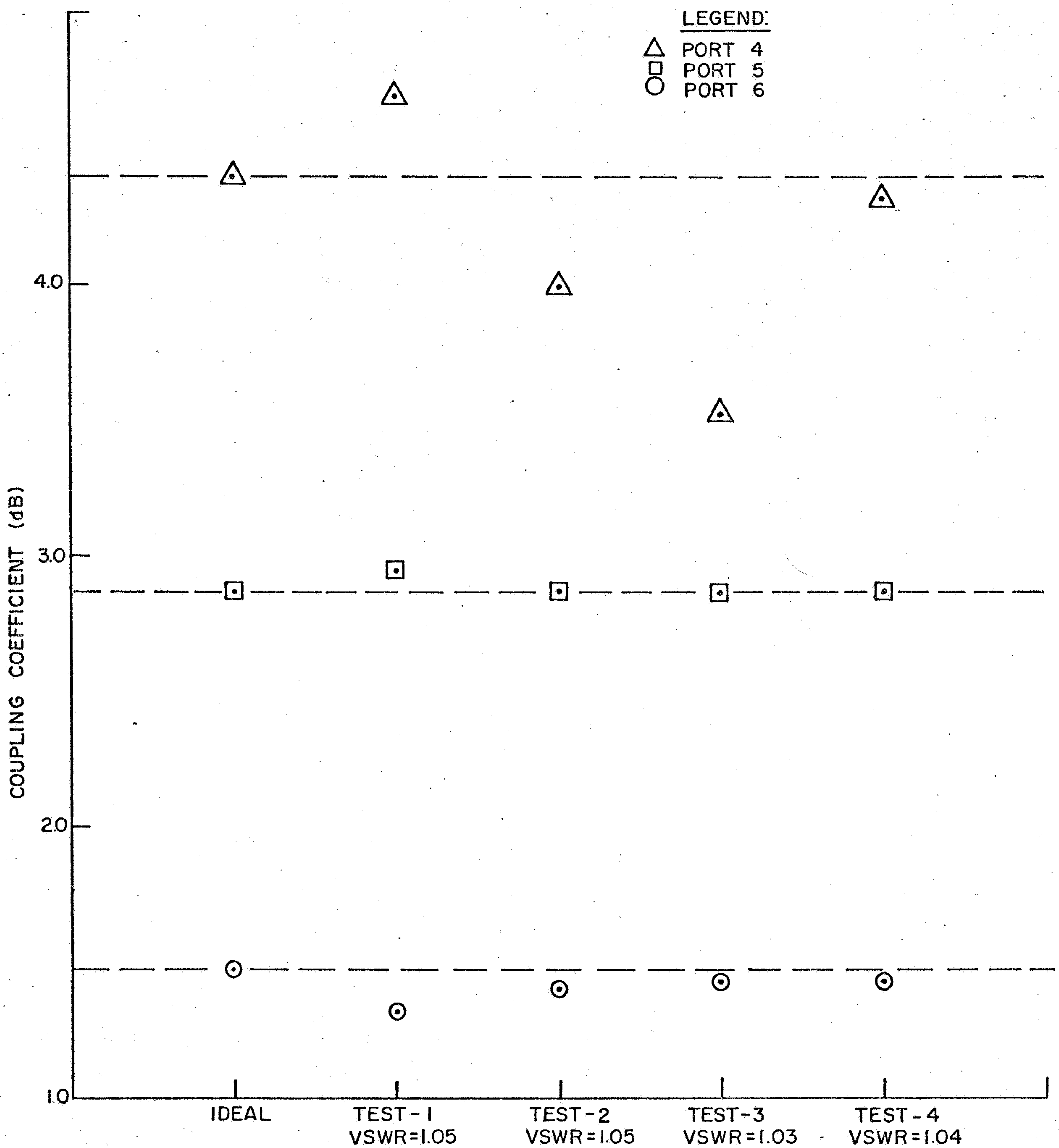

FIG 8 – TEST SECTION # 2

Shims are now being fabricated with slots at ports 3, 4 and 5. It is expected that all of the ports will be fabricated and tested during the next period. Once the correct slot size for each port is known, two additional series feed sections will be adjusted in a similar manner. These three identical units will then be used to test two filled rows of horns as soon as the phase shifters are delivered.

With the type of broadwall coupling being used, a twist is required between each port of the principal feed and each secondary feed line. Since a continuous twist in this waveguide size requires about $1\frac{1}{2}''$ of length, an investigation of step twists was made. In this period a step was designed and fabricated which would seem to be of the absolute minimum length. It was decided that adequate performance over the required bandwidth could be achieved using a three step twist. Since the output of the principal feed and the input of the secondary feed were equipped with flanges, the steps could be introduced by inserting between the two cross polarized flanges, two quarter wavelength sections of waveguide inclined at the appropriate angles. This approach then adds only 0.211" to the overall length. Bolting the assembly together requires only minor modifications to the holes in the flanges, and locating pins are used to assure proper alignment. The test section which was made up for initial measurement had a VSWR of less than 1.1 over the 33 to 37 GHz range and measured 1.06 at the design frequency of 35 GHz.

3. OPTICAL FEED SYSTEM

A parallel development to the series feed system involves a quasi-optical power distribution system. This will involve the use of a large illuminating aperture and a 49 element collecting aperture. Some of the fabrication and analysis of this approach has been completed in this period.

3.1 Lensed Illuminating Horn

The concept of the optical feed system is illustrated by the drawing of Figure 9. The power which would be radiated by the large illuminating horn is immediately intercepted by the array of smaller horns and brought back to standard waveguide for phase shifter operation. There are several yet to be answered questions here in terms of efficiency matching of the structure, etc. These will be answered experimentally.

One does know that in an unperturbed condition, a standard pyramidal horn of the type depicted here will have a maximum phase variation, T, across the aperture (where T is measured in wavelengths) of

$$T = \frac{L - \left[L^2 - \left(\frac{a}{2}\right)^2\right]^{\frac{1}{2}}}{\lambda}$$

where L= the slant length of the horn to its phase center

a = the width of the aperture

(Note this is a spherical approximation to the actual parabolic phase variation, but is valid for flare angles of less than 60°)

One must compromise then between the desired flatness of the phase front desired and the axial length of the horn which can be tolerated. For the development here, an axial length of 8" was chosen which results in an uncompensated phase variation of 0.32λ. (Once again we are working under the constraint that the profile of the feed should not exceed that of the 16λ square array. In this case, for convenience in later testing, they have been made precisely equal.)

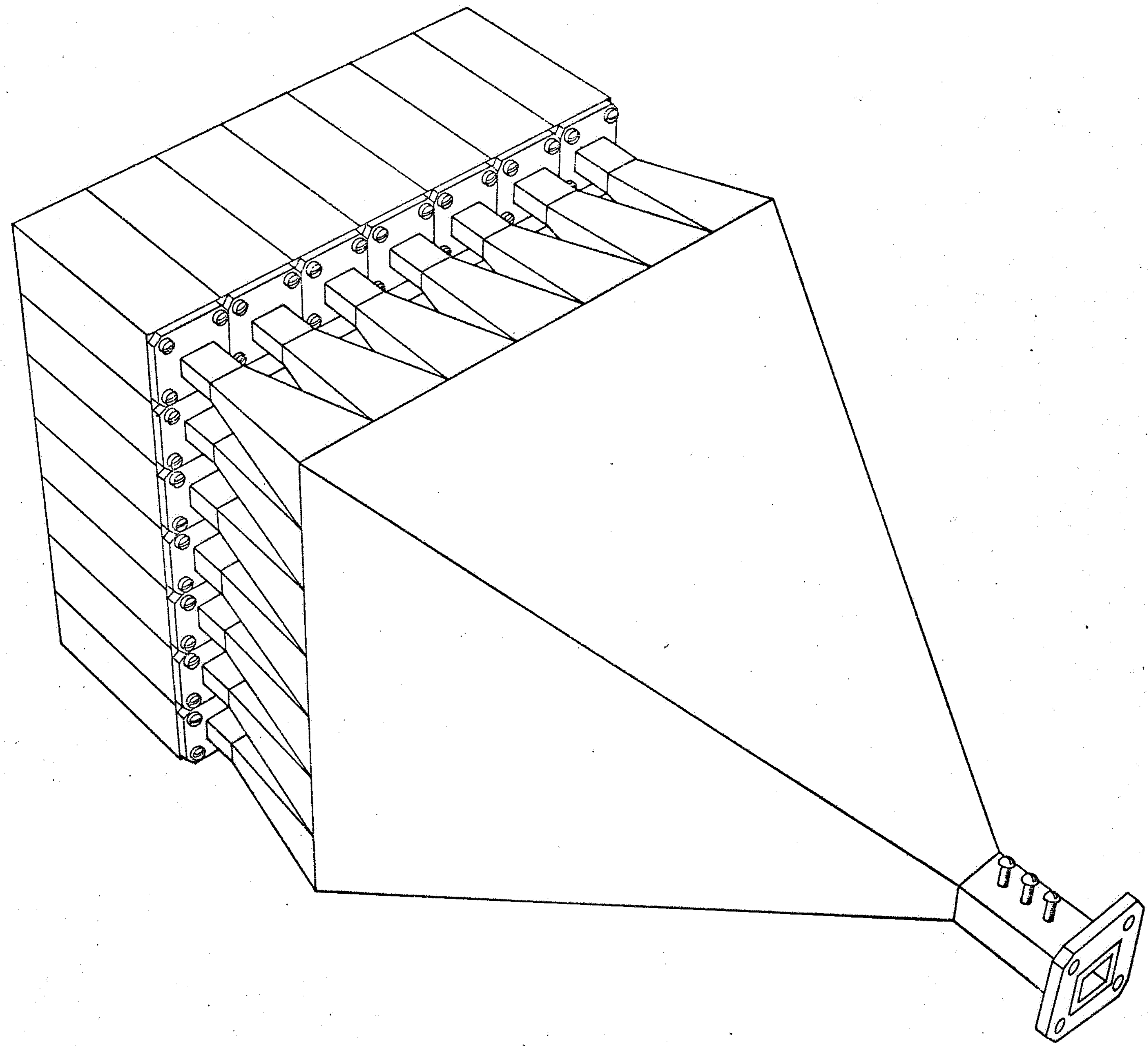

FIG. 9 - FEASIBILITY MODEL OF OPTICAL FEED

It is not known precisely at this time how this unperturbed field will be modified by the presence of the other horns at the aperture plane. It would seem that the optimum one could do would be tailor the phase variation across the large aperture to be the conjugate of that across the smaller horns. This is virtually impossible. The next best thing for an experimental development would seem to be that of having a uniform mismatch at every horn, i.e. a planar phase front. To this end, a phase compensating plano-hyperbolic lens has been designed for use with the horn. The hyperbolic surface of the lens is determined by the equation

$$(n^2 - 1) X^2 + 2f X(n-1) y^2 = 0$$

where
- f = focal length
- n = index of refraction of the lens material
- X = dimension parallel to the horn axis
- y = dimension normal to the horn axis

For this test, the lens was fabricated from Rexolite. The completed horn-lens assembly is shown in Figure 10.

3.2 Input Array for Optical Feed

Having, in theory, established a flat phase characteristic across the aperture, the next problem is that of determining the necessary sizes for the small horns in the input array. Although these apertures are not really large compared to a wavelength, an intercepted area approach may still be sufficiently accurate for design purposes, and this approach is currently being pursued.

For either the optical feed or the series feed, the final radiating aperture will be the array of uniform horns. These elements have been fabricated and are shown in the photo in Figure 11. Knowing the amplitude characteristics of the pyramidal feed horn, one can then

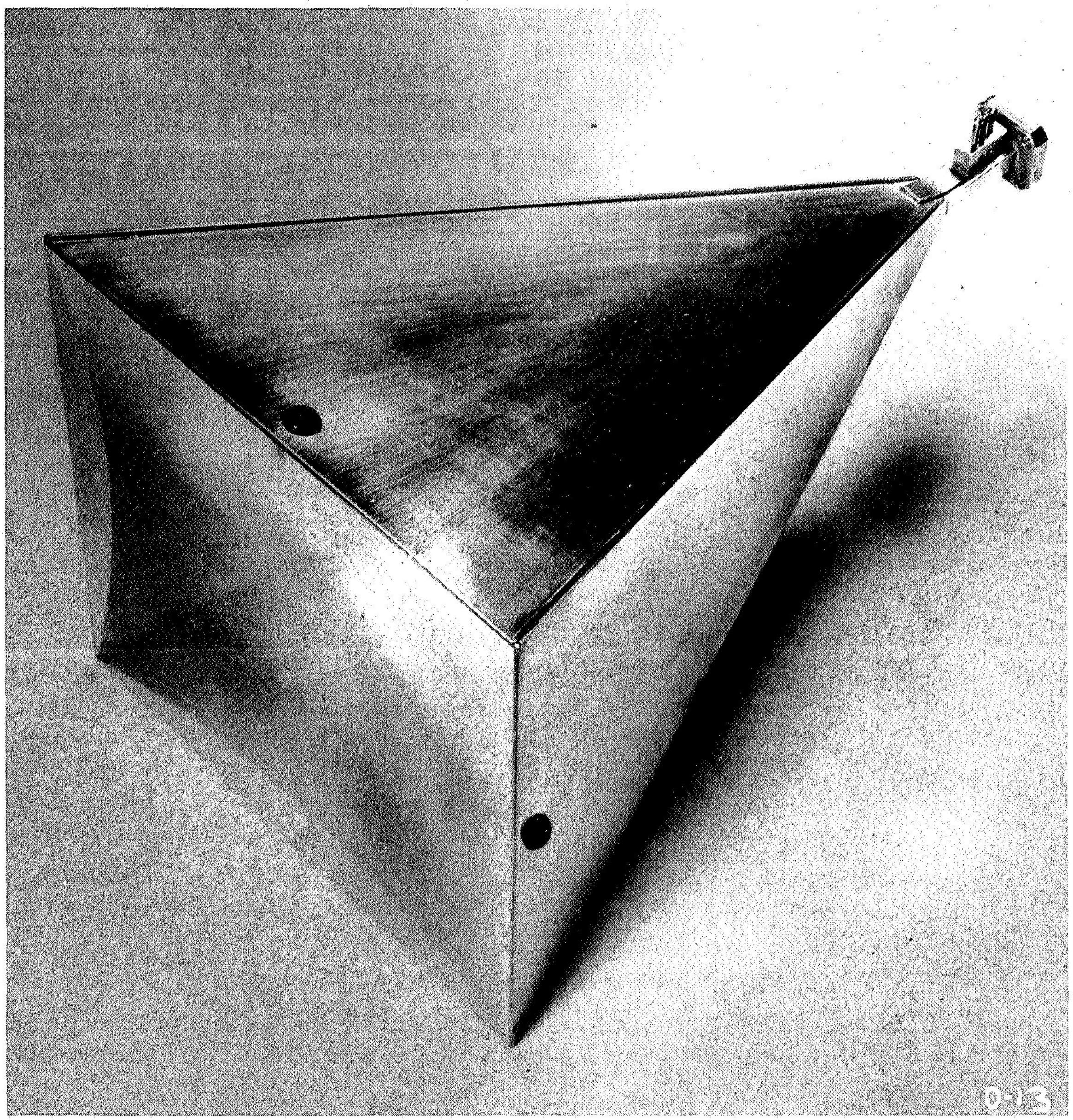

FIG. 10 - LENSED OPTICAL FEED HORN ASSEMBLY

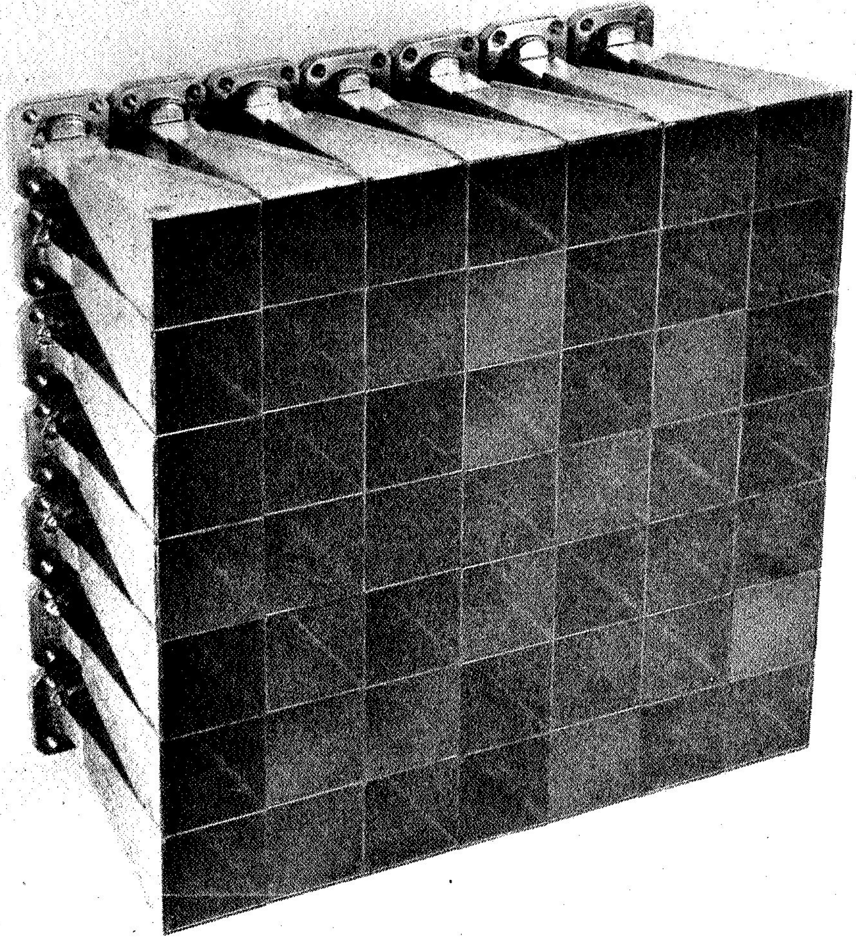

FIG. 11 - 49 ELEMENT UNIFORM ARRAY

calculate, on a purely geometrical basis, the amounts of energy each of these uniform horns should intercept (losses being neglected). The validity of such a calculation can then be verified experimentally, and this will be accomplished in the coming period. It will be done by terminating 48 horns and measuring the output from one. If the data and theoretical values coincide within the limits of experimental error, a non-uniform array of asymmetric collecting horns will be evaluated which would intercept power from the optical feed horn to effect the desired cosine on a pedestal distribution (see Figure 12). The dimensions of the mouths of these horns have been calculated (see Appendix). However, a problem arises in feeding these horns if the uniform spacing of waveguide axis is to be maintained. In the envisioned array it would be necessary to incorporate either asymmetric pyramidal horns or waveguide bends which would provide an offset in both the E and H-planes. At first glance the asymmetric horns appeared to be more desirable from the standpoint of ease of fabrication. The calculations show, however, that this asymmetry would probably introduce some severe matching problems in that the phase fronts across these horns would be tilted to quite an extreme degree. The uniform phase front then would not be a good approximation to the ideal.

Since, in one plane, the amplitude across the optical feed horn is cosinusoidal, and the desired output is a cosine on a pedestal, the horns at the edges will have to be quite large in order to furnish the pedestal, whereas the central horns will be approximately uniform in this dimension to preserve the cosine shape. It is this large outer horn which introduces the considerable asymmetry.

In the other plane, the asymmetry occurs in the opposite sense. Since the amplitude is uniform, the center horn must be the largest, tapering in size to the outer edge. If the horns are then made as symmetrical pyramids, there will be the requirement of the two

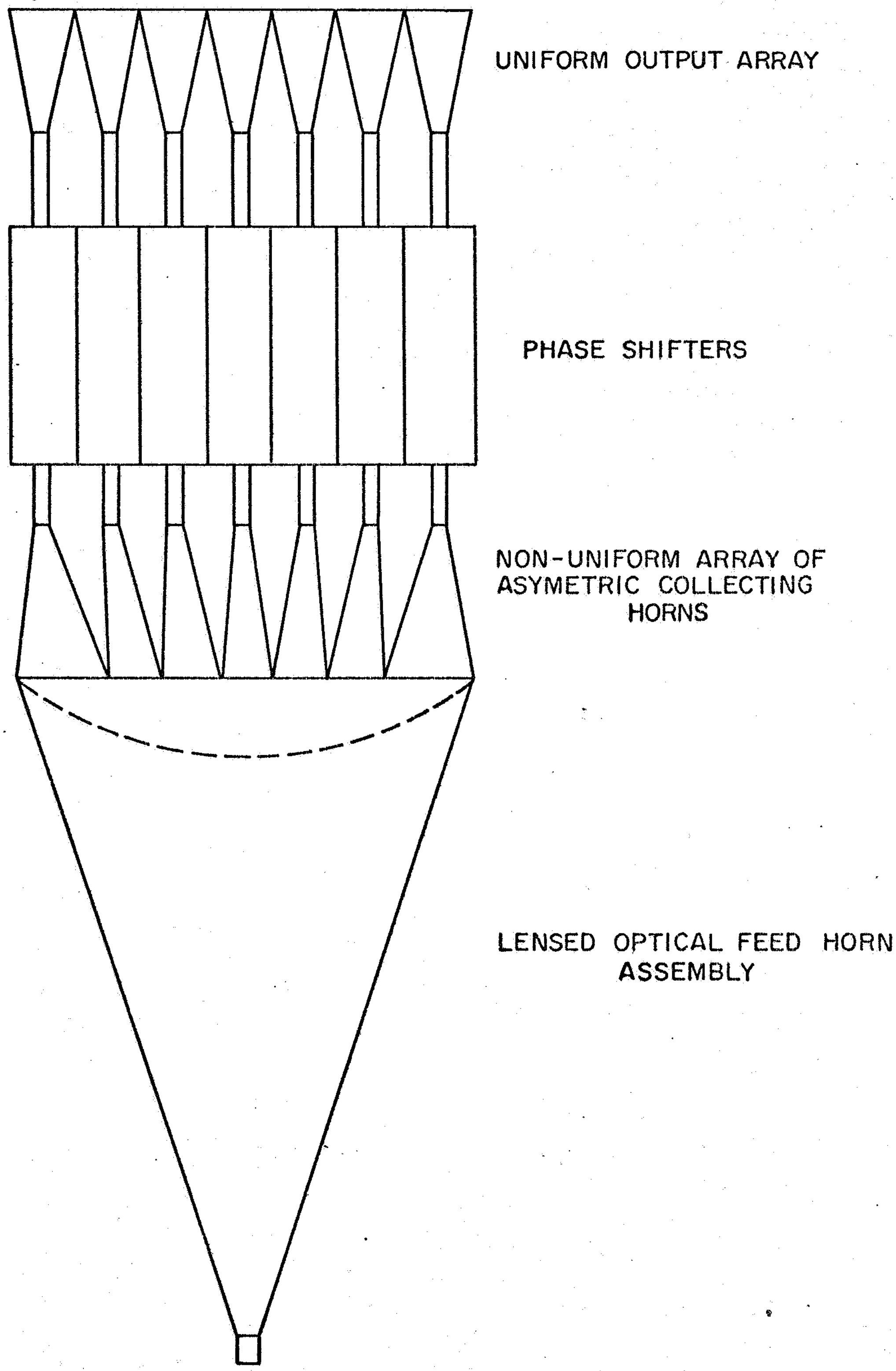

FIG. 12 – FEASIBILITY MODEL OF OPTICALLY FED ANTENNA ARRAY.

dimensional waveguide offset to properly align the waveguide axes. The extent of the offset is shown by placing the overlay, which represents the apertures of the non uniform array of collecting horns, on Figure 13 (the waveguide feed locations for the uniform output array).

This approach will probably introduce less loss and a typical offset bend is presently being fabricated for evaluation during the coming period.

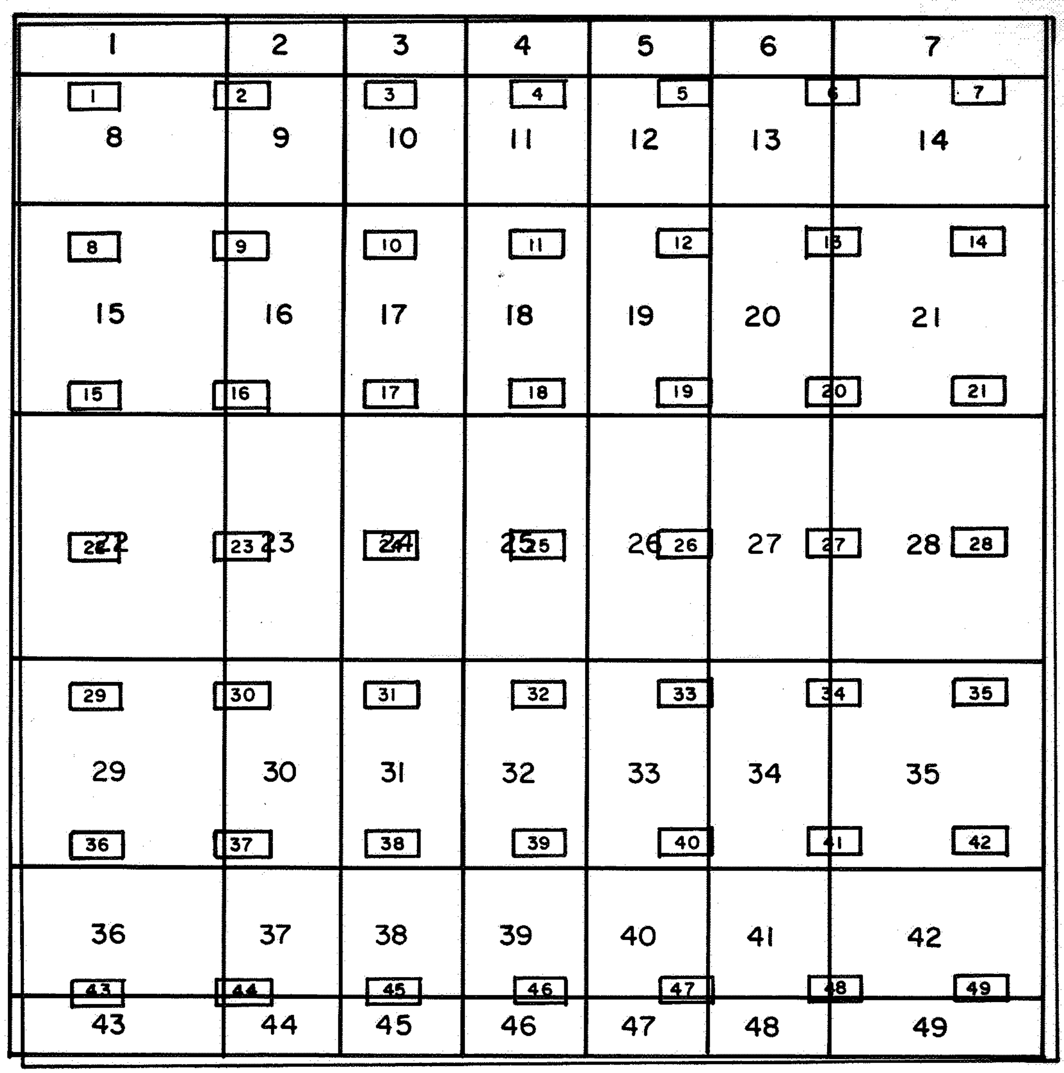

FIG. 13 - WAVEGUIDE FEED LOCATIONS FOR UNIFORM OUTPUT ARRAY

4. NEW TECHNOLOGY

During the period covered by this report, there have been no inventions, discoveries, or innovations which may be considered under the New Technology clause of the contract.

5. PROGRAM FOR THE NEXT INTERVAL

During the next quarter, work will be continued on the development and testing of the feasibility model of the antenna.

The final design of the couplers in the series feed sections and testing of these sections should be completed as should the testing of the optical feed horn. Analysis of the results of the latter tests will be performed and, pending the outcome, a compensated, non-uniform array of horns will be fabricated.

Antenna patterns of two completed rows of horns will be measured as soon as the phase shifters are delivered and tests will be performed to determine steering accuracy.

APPENDIX: CALCULATIONS ON THE OPTICAL FEED SYSTEM

A. Power Expectations from a 49 Element Uniform Array

Since the field in the waveguide feeding the optical horn is cosinusoidal across the H-plane, the power distribution at the aperture will follow a $\cos^2$ curve. Therefore, to calculate the power levels which can be expected across the H-plane of the uniform receiving array the following formula is used

$$P = \int_a^b \cos^2 \theta \, d\theta = \frac{\theta}{2} + \frac{1}{4} \sin 2\theta$$

Substituting for the case in question this becomes

$$P = \int_a^b \cos^2 \frac{\pi y}{16\lambda} dy = \frac{y}{2} \Bigg|_a^b + \frac{4\lambda}{\pi} \sin \frac{\pi y}{8\lambda} \Bigg|_a^b$$

The limits of integration then become the edges of each horn i.e. for the 16λ aperture integration is performed from -8λ to $+8\lambda$.

In the E-plane of the optical horn and therefore in the uniform array the power level of each of the columns of horns will be constant Albeit different for each column. Therefore the relative power levels at each horn are known once the input power is specified.

B. Compensated Non-uniform Array of Horns

To achieve the desired side lobe level for the output array it is necessary to illuminate it with a cosine on a pedestal type distribution. Specifically, the power taper should be a cosine taper with a 10 dB difference from center to edge. For the envisioned 49 element square array this leads to power level ratios of:

.222 : .555 : .870 : 1 : .870 : .555 : .222

It is necessary, then, to transform the output of the optical horn from the simple cosine taper across the H-plane to the cosine on a pedestal taper by means of changing the size of the horns in the array so that the received power is in the above ratios.

In the previous paragraphs it was stated that the power distribution across the aperture could be given by:

$$P = \int_a^b \cos^2 \theta \, d\theta = \frac{\theta}{2} + \frac{1}{4} \sin 2\theta$$

If the limits a and b are the end points of the curve i.e. the edges of the array then

$$P = \int_a^b \cos^2 \theta \, d\theta = \frac{\pi}{2}$$

or

$$P = \frac{16}{\pi} \int_{-8}^{+8} \cos^2 \frac{\pi y}{16} \, dy = \frac{16}{\pi} \left[\frac{\pi}{2}\right] = 8$$

This can be thought of as the total area under the curve given by $\cos^2 \frac{\pi y}{16}$ from -8 to +8. The problem is now one of finding the intercepts of the curve which would define areas in the prescribed ratios.

Now the sum of all the areas must equal the total area. Thus:

$$k \left[1 + 2 (.870) + 2 (.555) + 2 (.222)\right] = 8$$

where k is some constant

Then $k = 1.8631$

Also

$$P = \int_a^b \cos^2 \frac{\pi y}{16} \, dy = \frac{y}{2}\Bigg|_a^b + \frac{4}{\pi} \sin \frac{\pi y}{8} \Bigg|_a^b$$

So the first intercept can be found by solving

$$\frac{y}{2}\Bigg|_{-8}^{-b} + \frac{4}{\pi} \sin \frac{\pi y}{8} \Bigg|_{-8}^{-b} = .222k = .4136$$

The simplest approach to obtain a solution of this equation is the graphical approach

When this was accomplished and the upper limit was found it was used as the lower limit of the next integration and the process repeated. Thus:

$$\frac{y}{2}\Bigg|_{-4.730}^{-c} + \frac{4}{\pi}\sin\frac{\pi y}{8}\Bigg|_{-4.730}^{-c} = .555k = 1.0340$$

By this method the intercepts were found and these in turn can be interpreted as the dimensions in the H plane of the aperture of each horn in a row i.e. the first horn is $(8\lambda - 4.730\lambda)$ or 3.27λ and so on.

To achieve the cosine on a pedestal distribution in the E-Plane where each column of horns intercepts a constant amount of power it is a simple case of varying the size of the horn according to the prescribed ratio. So again

$$k[1 + 2\,(.870) + 2\,(.555) + 2\,(.222) = 5.4''$$

where 5.4'' is the length of a side of the array

Solving we get the E-Plane dimensions of the non-uniform array of horns

$$k = 1.2576''$$

Horns # 1 and 7 = .222 k = .2792''

Horns # 2 and 6 = .555 k = .6980''

Horns # 3 and 5 = .870 k = 1.0941''

Horn # 4 = k = 1.2576''